IWG @ F2F

November 15, 2016

Mark Bautz for

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Ralf Heilmann, Ralph Kraft & Randy McEntaffer

Overview

- Activity
- Instrument State of the Art
- Plans
- Questions for STDT

Activity

- Biweekly telecons since August
- Accomplishments
  - Ratified Charter
  - Defined current state of the art for μCal, HDXI and XGS
  - Specified sub-charters for each instrument group
  - Invited selected experts to join
  - Addressed some questions from the Chair (work in progress)

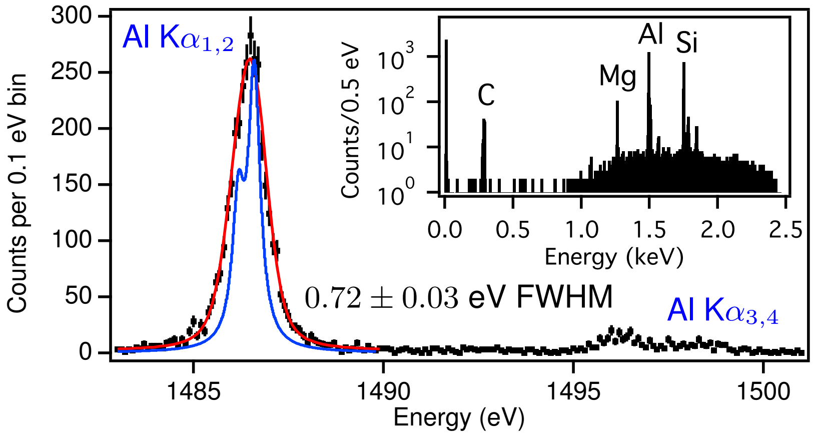
Instrument State of the Art

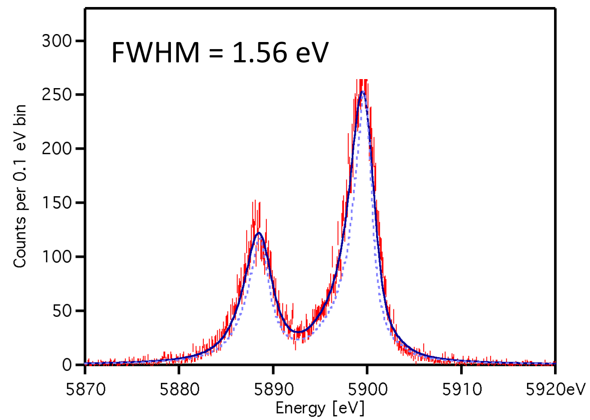
- Here: State of the Art ≡ shown once in lab.
  - Generally only as proof-of-concept, rather than flight ready component/system, and
  - There are known performance tradeoffs, but
  - Not necessarily the boundary of what's possible for XRS
- Micro-calorimeter (Bandler/Figueroa):
  - https://drive.google.com/drive/folders/0B7glf1X5jW5IbEFBQTRCVE9oYmM
- High-Definition Imager (Falcone/Kraft)
  - https://drive.google.com/drive/folders/0B7glf1X5jW5IbEFBQTRCVE9oYmM
- X-ray Grating Spectrometer (McEntaffer/Heilmann)
  - https://drive.google.com/drive/folders/0B7glf1X5jW5IbEFBQTRCVE9oYmM

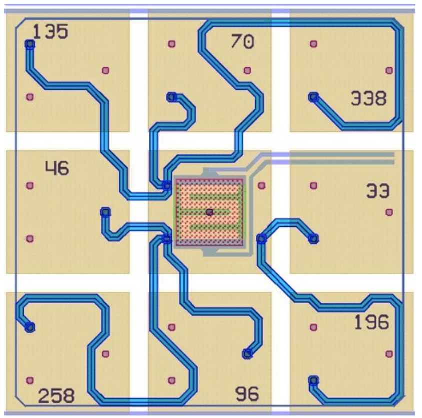
Microcalorimeter: Current best laboratory performance

Best energy resolution TESs (MMCs also being developed) [all FWHM]:

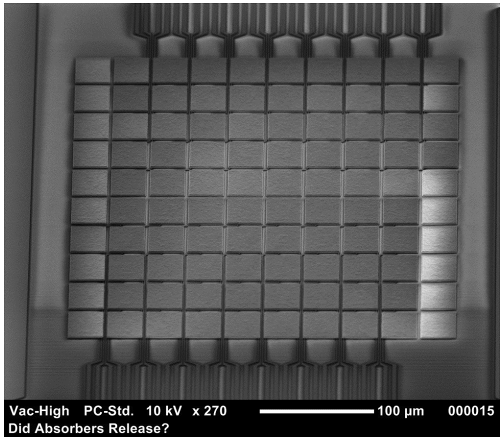
Energy Up to 1.5 keV = 0.7 eV ; up to 6 keV = 1.6 eV ; for 9-absorber hydras, rms = 2.4 eV





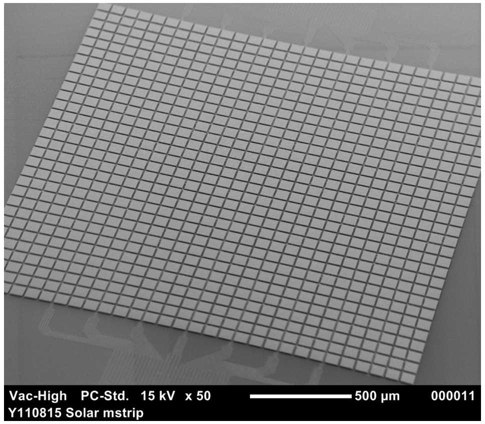


Smallest pixel pitch:

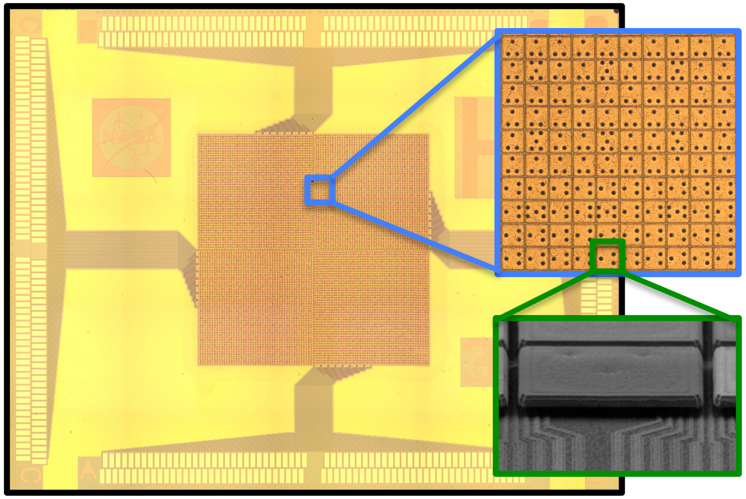


Array of single pixels
- on 35 um pitch, 0.7" for 10 FL
- up to ~2000 single pixels possible

Largest Arrays:



32x32 array of single pixels
- on 75 μm pitch

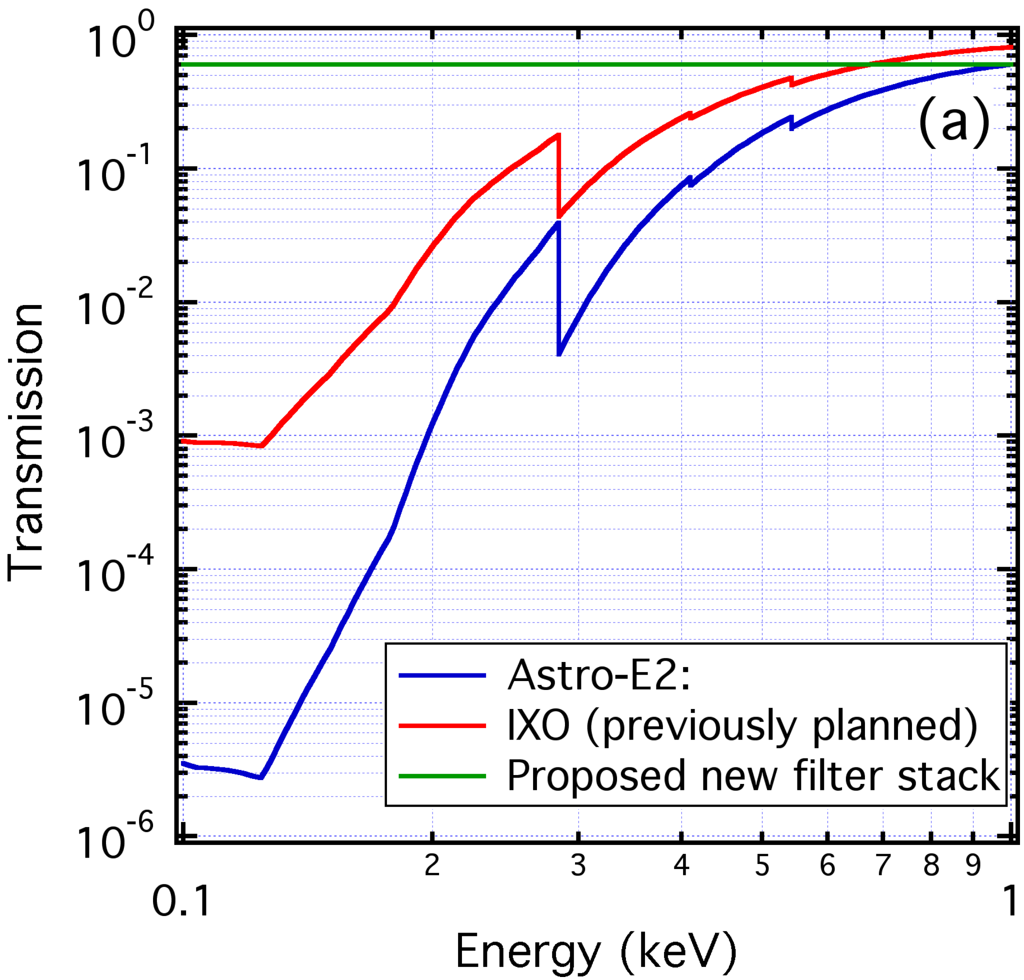


96x96 array (9216 pixels) on 75 μm pitch
- 32x32 array of 3x3 Hydras

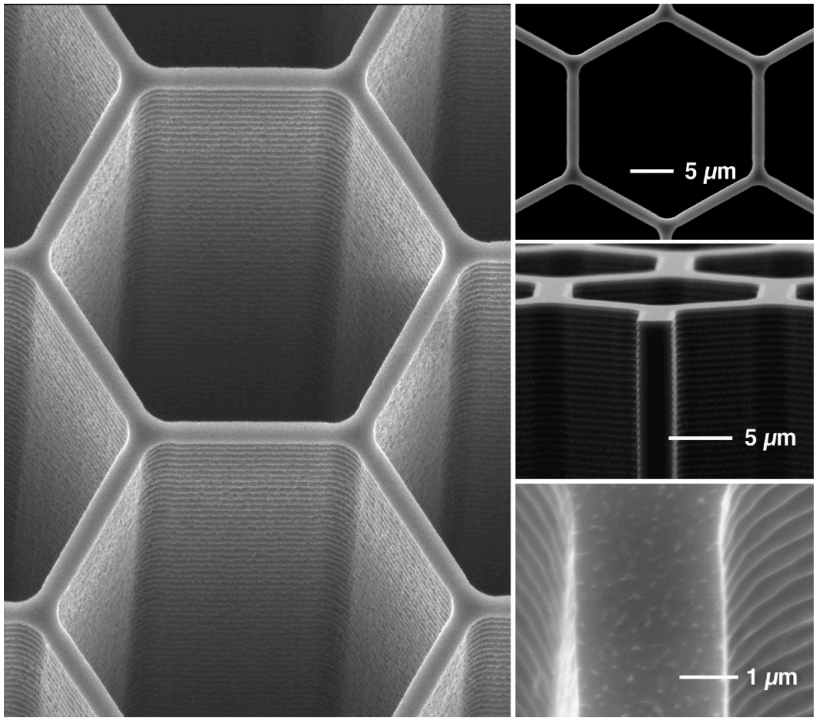
NB: Assume: XRS ~ 100 k pixels

Low energy cut-off & small-hole *"grill"* filters

May open up the filter transmission area under 1 keV by orders of magnitude, at the expense of some 6 keV throughput.



Transmission of traditional filter stacks drops substantially below 1 keV



SEM image of prototype hexagonal small-hole filter

Microcalorimeter Tradeoffs (1/2)

General Trade-off: Energy Resolution vs. FoV vs. Count Rate

1. FoV / Number of pixels limited by large number of factors (back-up slide), three most important being:

i. Number of multiplexed pixels per read-out channel:

- Code division multiplexing (CDM):

  ~ 20-80 pixels per channel, ~ 100 read-out channels possible

- Microwave multiplexing (u-wave MUX)

  ~ 500-1000 pixels per channel, ~ 4-8 read-out channels might be possible

=> ~ 2000 – 8000 sensors, depending upon bandwidth (count rate) requirements

- Pixels per read-out channel (CDM or u-wave MUX) scales linearly with energy range!

ii. **For a given pixel pitch, sufficient space required for low cross-talk wiring** between pixels within the array

- Depends on pixel pitch

iii. How many pixels can we sub-divide each sensor into (Hydra)?

- Hydras help massively with (ii), increasing pixel number without increasing number of wires within array

Microcalorimeter Tradeoffs (2/2)
General Trade-off: Energy Resolution vs. FoV vs. Count Rate

2. Energy resolution of pixels will be between 0.5 eV and 5 eV, depends upon:

- Total pixel/hydra size - ΔE scales roughly linearly proportional to total size of single pixel or hydra
- Hydra factor - ΔE degrades resolution by ~ 20-50%, depending on hydra design, for a fixed total hydra size
- Energy range - ΔE scales roughly as (energy range of hydra)^0.5.
- Degradation due to read-out – none needed intrinsically, but can trade with MUX factor/FoV.

3. Minimum angular scale of pixel size:

- Pixel pitches from 35 um to 100 um
  – as pitch decreases, wiring for fewer close-packed pixels/hydras fit within array
- Angular scale of pixel depends on focal length: (typically 1" for 50 um pitch and 10 m focal length)

4. Count-rate

- **Demonstrated operation up to 1000 cps/pixel**,
  - 2.3 eV FWHM seen at 100 cps (99.6% throughput), for a fast pixel
- Typically considering ~ 20 cps maximum per hydra (~0.2 mCrab for 2m^2 area)
- Option to degrade energy resolution as count rate increases (record length decreases); alternatively bandwidth used increases and MUXing factor/FoV decreases.
- Number of pixels (hydras) per read-out channel scales linearly with count rate requirement.

https://drive.google.com/drive/folders/0B7glf1X5jW5IbEFBQTRCVE9oYmM

HDXI Status, Future Developments, and Fundamental Trade-offs for the sensors and electronics of the HDXI

Strawman requirements – to be modified by STDT!

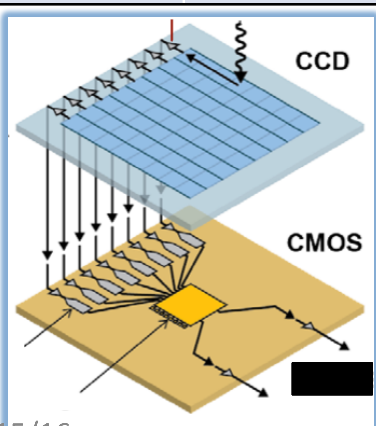
HDXI Parameters	
Energy Range	0.2 – 10 keV QE > 90% (0.3-6 keV), QE > 10% (0.2-9 keV)
Field of View	22′ × 22′
Pixel size	≤ 16 × 16 micron (≤ 0.33 arcsec)
Read noise	≤ 4 e^-
Energy resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Frame rate	> 100 frame/s (full frame) > 10000 frame/s (windowed region)
Radiation tolerance	10 years at L2

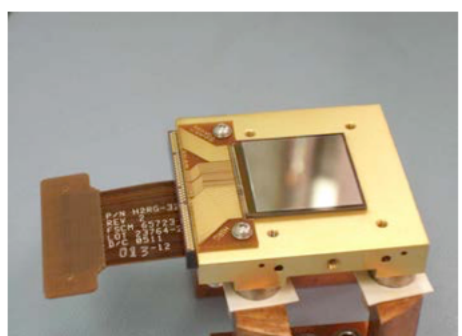
Three active pixel sensor technologies currently under discussion by IWG

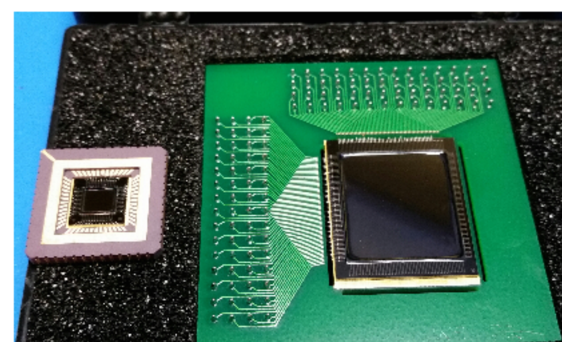
- •Digital CCDs (LL/MIT)
- •Hybrid CMOS (Teledyne/PSU)
- •Monolithic CMOS (Sarnoff/SAO/MPE)

Additional Developments:

- •High Speed Event Processing Electronics
- •Ge detectors (?)
- •Event-driven detection (?)







HXDI: Current State of the Art

- All of the key requirements are met by one or more of the sensor technologies
- No single sensor meets them all – lots of work to do!

Key improvements over ACIS and EPIC

- Orders of magnitude higher frame rates (~1000 frames per second)
- Significantly improved radiation hardness
- Fully addressable (i.e. high speed windowing)
- Near Fano-limited resolution over entire bandpass
- Lower power
- Near room temperature operation
- Large format (up to 4Kx4K abuttable devices)

Key sensor trade-offs

1) Pixel size
   - Small pixel size to oversample PSF decreases energy resolution
   - Small pixels increases number of sensors required to fill focal plane
2) Deep Depletion
   - Thick devices improve QE above 5 keV but may degrade energy resolution below 1 keV
3) Higher Frame Rates
   - Mitigates pileup and *may* improve background rejection, but increases complexity and power of read out electronics & may degrade energy resolution
4) Maturity vs performance

X-ray Grating Spectrometer State-of-the-Art

- Key performance parameters (demonstrated):

	Resolving Power ($\lambda/\Delta\lambda$)	Diffraction Efficiency	E_{min} [eV]	E_{max} [keV]
CAT	> 10,000	32% (@ 0.5 keV)	Detector QE limited	> 1.5*
OPG	~3,900**	>35% from 0.5-1.0 keV	Detector QE limited	Limited by reflectivity of coating at graze angle (typically ~2 keV)

*Pt coated **Limited illumination

X-ray Grating Spectrometer State-of-the-Art

Caveats/Tradeoffs:

- Highest performance parameters not achieved in a single device.
- Tradeoff between resolving power and effective area due to sub-aperturing. Maximizing both requires multiple readouts.
- Higher efficiency possible, but structures cause blockage. Effective area /geometrical area ~ 30-35% max.
- Tradeoff between resolving power (~blaze angle) and E_{max} due to graze angle.
- Resolving power limited by optical design/aberrations.
- Link:
  - https://drive.google.com/drive/folders/0B1my4rwDLuZscUhvYU1Xa3ZMYnc

Plans: Common Elements

- Iterate with STDT to define requirements
  - Establish baseline & goals
  - Identify, develop & articulate tradeoffs for STDT
- Support response function development
- Work with PCOS to establish technology development priorities for APRA & SAT
- Produce timelines and plans for technology development required for concept study
  - Requires current technology readiness assessment
  - Target: TRL 5 by Decadal; TRL6 by PDR
- Support ACO mission studies
- Broaden community involvement in IWG
  - Encourage community interest
  - Identify and meet needs for professional support

Plans: Instrument-Specific

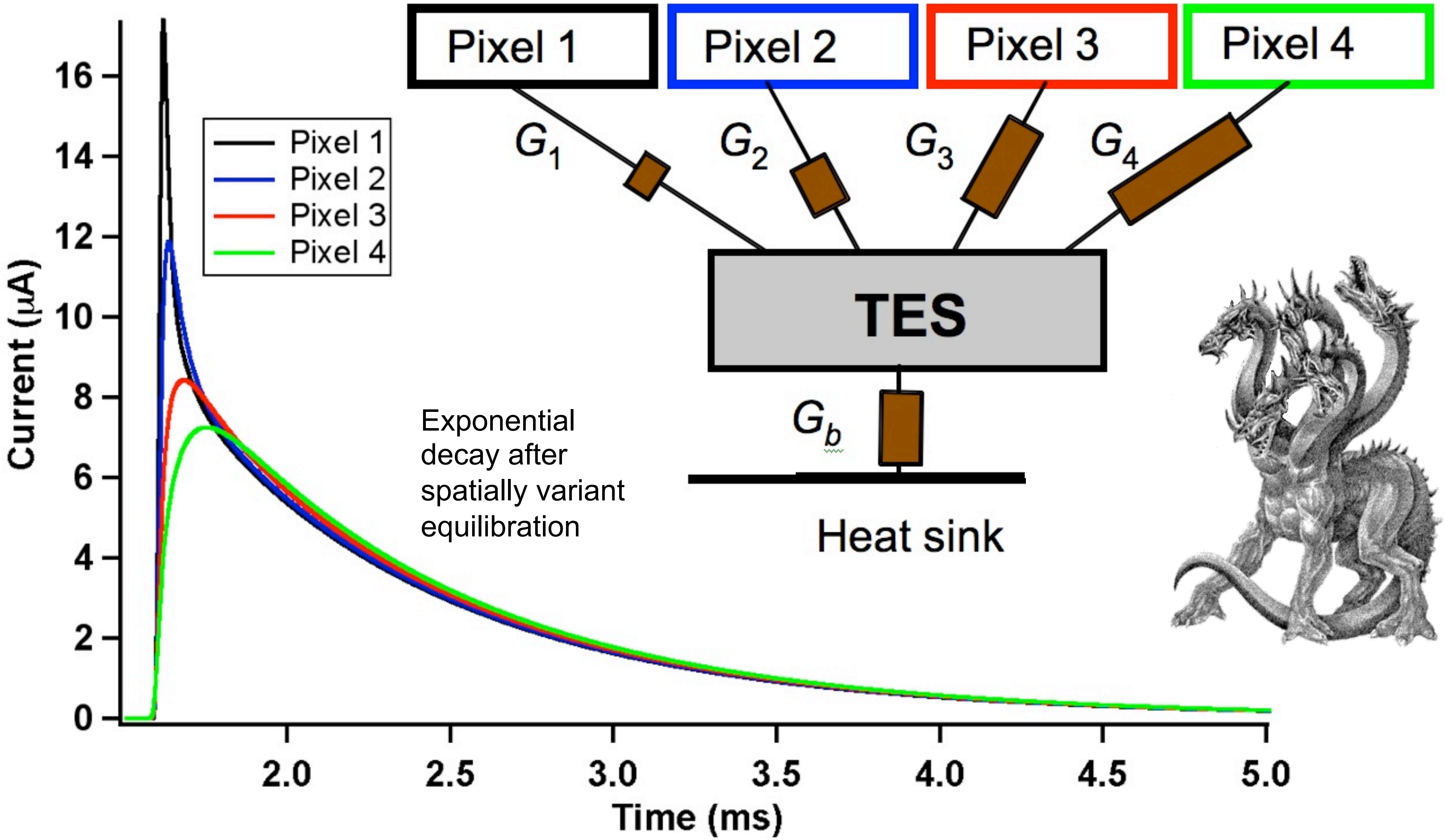
- Micro-calorimeter
  - Evaluate new readout multiplexing technologies
  - Assess U.S. cryostat options & technology
  - Assess high-throughput blocking filters
- HDXI
  - Refine Hybrid/Monolithic/DCCD comparison
  - Evaluate detector electronics requirements & readiness
  - Determine instrument design vs non-X-ray background trades
  - Work with XGS on grating readout requirements & configurations
- XGS
  - Develop detailed ray-tracing analysis
  - Work with HDXI on grating readout requirements & configurations

IWG questions inspired by SWG presentations

- Would smaller pixels (e.g. 0.5”-0.7” vs. 1”) in a central region of the μCal FOV be desirable?
  - If so, how large should this region be?
- Is it worthwhile to trade μCal FOV for improved energy resolution?
  - e.g., 3eV FWHM over 3’ rather than 5 eV over 5’ ?
- Is it worthwhile to increase grating E_{max} from 1.5 keV to 2.5 keV at the possible expense of low-energy efficiency loss of 20%?
- Would a larger FOV for the HDXI be desireable?

Back-up

Multi Absorber TES “Hydras” - 1 TES, 4 absorbers
– increase field of view for a fixed number of read-out channels



Also works with MCCs

Top 10 constraints to number of pixels, size of array and array layout, other than energy resolution and count rate requirements, and general TRL

1. How many pixels per read-out channel can be read out without energy resolution degradation? 80 per CDM column? 1k per u-wave channel (needs to be studied).

2. Ability to fabricate sufficiently large arrays with sufficient space for required low cross-talk micro-strip wiring fitted between pixels. – Being developed.

3. How many pixels can we sub-divide each Hydra into?

4. Whether size of FPA becomes too large, considering area of read-out

5. Can we construct an aperture design (filters etc.) for the larger FoV's.

6. How many read-out channels can be managed in terms of heat loads and FPA complexity – TBD – study needed. 8 u-wave channels?

7. Power load/cost from number of electronics channels ? (Depends upon approach taken, study needed for uwave approaches).

8. Ease of calibration

9. Pulse processing complexity / feasibility – not likely to be a constraint at XRS count rates

10. How to make sufficient reliable contacts between detector chip & low-temp. read-out?
    - Bump bonding likely best approach

What could be done as part of XRS microcalorimeter IWG efforts:

1. Work with STDT to establish baseline and goal requirements for a microcalorimeter instrument for XRS. Discuss and evolve trade-offs of potential microcalorimeter focal plane designs, taking into account the desire for the greatest scientific capability and the level of difficulty to develop. Consider also the TRL, efficiency of resources used, and scale of cost.

   - Develop time-table and process for evolving design
   - Clarify the driving science requirements for instrument.
   - Discuss trade-off of pixel size versus FOV, energy resolution versus FoV, count rate capability, focal plane layout and potential hybrid designs.
   - Work with XRS SWG to evolve an XRS microcalorimeter simulator, for investigating potential science targets, including effects of dithering.
   - Establish baseline and goal instrument requirements.
   - Develop TRL definitions and timetable for evolving to TRL-6 by PDR, with guidance on the most appropriate resource levels needed.

2. Provide inputs to NASA announcements of opportunity for ROSES/SAT. Evolve technology gap descriptions with PCOS. Encourage further research development on the development of larger arrays, smaller pixels and wiring, and more capable read-out electronics.

3. Analyze new microcalorimeter read-out techniques, and their potential impact on what might be achievable. Carry out study of what development is necessary for envisaged read-out electronics for space flight.

4. Carry out a study on the most appropriate size, mass, power and cost of a U.S. microcalorimeter cryostat for XRS.

5. Participate in ACO costing/mission design exercises, and NASA center instrument design exercises.

What could be done as part of XRS Grating Spectrometer IWG:

1. Work with STDT to establish baseline and goal requirements for a grating spectrometer for XRS:
   a) STDT to define the driving science requirements
   b) IWG to define basic designs that meet (or approach) these requirements
2. IWG to identify and describe basic trades (effective area vs. resolution, one vs multiple readouts, etc.)
3. Define TRL of all key components. Develop path to TRL5 before 2020 Decadal and comprehensive plan to get to TRL6 by PDR.
4. Identify technology needs, gaps, and funding requirements to reach above milestones. Communicate to PCOS/SAT.
5. Identify readout technology and work with appropriate sensor experts to define the readout.
6. Develop ray-trace models that can support detailed trade studies.
7. Identify potential layout constraints due to other focal plane instruments.
8. Determine what level of engineering support is required to support mission concept studies.
9. Participate in all ACO costing/mission design exercises.

What could be done as part of Si Sensor (SiS?)/HDXI IWG:

1. Work with the STDT to establish baseline instrument and science requirements
   a) STDT to define science requirements – at first F2F? Probably only preliminary – we can really get started once we have these
   b) SiS IWG needs to outline/define technical trades (e.g. energy resolution versus read out rate, energy resolution versus pixel size, etc.) – I think we should try to do this (at least first cut) BEFORE the F2F in Nov. and that this should be part of the IWG presentation.
2. Clarify future research/technical development path for both sensor and drive/readout electronics. This will depend to the science requirements sent down by STDT. There are presently 3 groups working on SiSs with somewhat different goals. Is there anything we collectively are not doing that XRS will need? Aggressively work with NASA (HQ and PCOS office) to ensure that our technology needs and funding requirements are well-known (and met!). Do we want to push the need for an event-driven system?
3. Participate in all costing/mission design exercises that the STDT does with the ACO. We will need to provide key inputs related to costing and trade-offs (e.g. impact of number of sensors, data rate, cryogenics -> cost/mass/etc.)
   a) RPK – I was unhappy with costing of ACO study and want to look at this more carefully and assess/compare with recent comps (TESS, Euclid, Kepler, etc.)
   b) Camera design for previous ACO study was very generic. Do we need to improve this? Does this matter?

4. Define TRL of all key components and determine what it would take to get everything to TRL 5 before 2020 Decadal. Develop comprehensive plan to get to TRL 6 by PDR.
5. Determine what level of engineering support (if any) is required for mission concept studies. We will probably need to get some level of internal MIT/SAO/PSU funding to support this – B&P/IR&D.
6. Define what other members of the SiS/HDXI IWG are going to do. This is still at present ill-defined.

Community Involvement Plan

- Broad (PCOS, HEAD) call for community for participation imminent
- Link on IWG web page to be live this week
  - Instrument sub-charters describe plans
  - Form requests input on interests and contributions